Biomass, litterfall and the nutrient fluxes in Chinese fir stands of different age in subtropical China

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Abstract: Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), a fast-growing, ever-green conifer tree with high yield and excellent quality, is the most important tree species of timber plantations in subtropical China. We investigated the characteristics of biomass, litterfall and nutrient fluxes in the 8, 14 and 24 year-old stands, representing the young, middle-aged and mature stands. The results showed that Chinese fir plantations in central Fujian province had high productivity, and the proportion of stem mass in total biomass was between 50%-70%. Chinese fir was low nutrient-return tree species with litterfall. Nutrient withdrawal from senescing needles was a strong age-dependence for nitrogen, phosphorous and potassium in Chinese fir. With a management system of such short-rotation and continuously pure-crop planting, harvesting timber can lead to great nutrient loss, which may be one of the causes for site degradation.

Keywords: Chinese fir; Biomass; Productivity; Litter fall; Nutrient flux

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Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), a fast-growing evergreen coniferous tree with high yield and excellent quality, is one of the most important tree species of timber plantations in South China. Chinese fir plantations range from about 20 to 30° N in latitude and 100 to 120° E in longitude, and its total area in China is around 9.11 million hectares (Li *et al.* 1997). Site preparation, fertilizer application and tending are often applied to raise timber production in intensively managed stands (Pan *et al.* 1983). Chinese fir stands reach maturity after about 25 years. It is common practice in China for Chinese fir plantations to be managed in a system of clear cutting, prescribing burning and successive planting (Yu 1997).

The production of organic matter, litter fall and the nutrient cycling have been ones of central subjects in forest ecology, and the understanding of these topics is an important basis for reasonable management of a stand (Rodin and Bazilevich 1967; Cole and Rapp 1981; Attiwill and Adams 1993). Only since the beginning of the 1980s, has the productivity and nutrient cycling been investigated in Chinese fir plantations (Pan *et al.* 1981; Pan *et al.* 1983; Feng *et al.* 1985; Nie 1994). These investigations demonstrated that the productivity, dry matter allocation and patterns of nutrient cycling in Chinese fir stands varied with climate conditions, site factors, stand age, silvicultural measurements, etc. (Pan *et al.* 1981, 1983; Feng *et al.* 1985; Nie 1994). Chinese fir is cultivated in broad areas in which climate factors vary greatly (Huang and Shen 1993). For the plantations of Chinese fir as an intensively managed ecosystem, available data is far enough to expound the patterns of biomass accumulation and nutrient fluxes with diversity of climates, soils and sites. In particular, a systematic study of dry matter allocation among biomass components and their relevant nutrient status is still rare in Chinese fir stands of different ages (Pan *et al.* 1981).

The retranslocation of nutrients from senescing tissues is considered as a mechanism for trees to adapt themselves to environments (Fife and Nambiar 1982; Bernier 1984; Aerts 1995). The quantity and ecological importance of nutrient withdrawal varies with tree species and sites, but no consistent pattern has been obtained by investigators (Van Den Driessche 1984; Helmisaari 1992; Ericsson 1994). The nutrient removal from senescing tissues has not yet been reported in Chinese fir stands, and the role of nutrient removal in sufficing nutrient requirements is unclear (Yu 1997). An investigation of nutrient resorption from senescing needles of different aged Chinese fir will bring some new understanding on the pattern and function of nutrient withdrawal.

Generally, plantations managed for short rotations are the most nutrient-demanding, and cause the greatest losses of nutrients from the site at harvest (Ericsson 1994). In the productive Chinese fir areas, the biomass could be about 280 tons per hectare with about 80% of stem mass (Pan *et al.* 1981). The impact of log on nutrient budget also needs to be discussed quantitatively because of higher

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stem biomass proportion in the total tree biomass and a shorter rotation for Chinese fir stands.

One of critical issues faced in Chinese fir plantation management is the decline of site productivity under traditional intensive regime, of which the imbalance of nutrients has been assumed to be one of potential causes (Wu *et al.* 1990; Ma *et al.* 1997; Sheng 1992). A project has been set up to aim at the mechanism of maintaining long-term productivity of Chinese fir plantations. In present study as part of this project, our major objectives are to elucidate the patterns of dry matter allocation, biomass increment and litterfall, and to show the characteristics of nutrient fluxes with these matter flows in Chinese fir stands at different age in Southeast China.

Materials and methods

Study sites

Field data were collected from Chinese fir plantations near the Youxi Ecological Research Station for Chinese fir (26º6′N, 118º12′E, about 200 m a.s.l). The Youxi County is in central Fujian Province, featured with low-mountain and hill land and a subtropical maritime monsoon climate. Annual mean precipitation is 1600 mm, and mean potential evaporation is 1323 mm. Annual mean temperature is 18.9ºC. Highest monthly mean temperature is 27.8 ºC in July, and lowest monthly mean temperature 8.9 ºC in January. The vegetation zone is characteristic of broad-leaved evergreens forest.

Three stands, ageing 8, 14 and 24 years and representing three development stages of stand (young, middle-aged, and mature), were chosen. All stands were established on the clear-cutting sites where previous crops were *Pinus massoniana* plantations. The site preparation included prescribing burning and digging a pitch. In 1997, the young stand was still at the initial density, but the middle-aged and mature stands had received the thinning of similar regime. Some conditions of three stands are listed in Table 1.

Table 1. Statistical properties for three experimental stands prior to field measurements (mean ± s.e., n=12)

Stands	Age (a)	Density (stems · hm^{-2})	Mean DBH /cm	Mean height /m
Young	8	3602±19	8.4±1.0	6.4±0.7
Middle-aged	14	1950±26	14.1±1.4	9.6±0.5
Mature	24	1775±31	15.8±1.9	12.8±0.9

All sites are located in an east-facing hillside, with elevations about 210 m a.s.l. The soils were silty loam oxisols developed on parent sandstone, with a depth of about 80 cm. The thickness of the forest floor was 7.5 cm in the young, 16 in the middle-aged and 18.5 cm in the mature stands, respectively. Some physical and chemical properties of surface soils are listed in Table 2.

Litter fall

Twelve litter collectors of 1 m × 1 m × 0.2 m were systematically installed within each stand. Litter was collected monthly from January 1997 to December 1998. In the laboratory, the litter was sorted into 4 fractions: branch, needle, flower and cone, and other. Dry weight of sample was obtained after oven drying at 80 °C to the constant weight. Sub-samples of each litter fraction collected in March 1997 were used for chemical analysis.

In addition, senescing needle and litter samples for chemical analysis were collected in December 1997 when litter fall peaked. Mature needles, over 3 year-old, from the middle crown of sample trees were taken to represent senescing needles

Table 2. Organic matter(OM), bulk density(BD) and nutrient concentrations on 0-20 cm soil layer in three stands(mean±s.e., n=12)

Stands	OM /mg· g^{-1}	BD /g· cm^{-3}	N /mg· g^{-1}	P /mg· g^{-1}	K /mg· g^{-1}	Ca /mg· g^{-1}	Mg /mg· g^{-1}
Young	35.1±0.6	1.11±0.10	1.3±0.12	0.34±0.04	24.0±0.4	3.5±0.2	3 7±0.4
Middle-aged	31.4±0.9	1.07±0.07	1.2±0.09	0.29±0.03	18.7±0.2	3.3±0.3	3.3±0.2
Mature	26.3±0.4	1.09±0.09	1.0±0.08	0.27±0.03	17.3±0.2	3.4±0.2	3.4±0.3

Biomass and its annual increment

Twelve 20 m × 5 m plots were selected in each stand of different ages. Total thirty-six plots were established in different aged stands. The height, the diameter at breast height, and the crown width of each tree in each plot were measured in January 1997. Four sample trees in each stands, which were outside and close to the sampling plots, were chosen with the same height and DBH as the mean height and DBH of trees in the stand. These trees were cut down and the roots carefully dug out. The roots were divided into different size groups according to Pan *et al.* (1981). The aboveground biomass of each sample tree was divided into stem wood, bark, cone, and 3 branch and needle classes according to age (Pan *et al.* 1981). All fractions were weighed in the field and then sub-sampled for determination of the dry weight and nutrient concentration. From these sample trees the mean biomass of trees in each sample plot was calculated. The biomass of each stand was then calculated by multiplying biomass of the mean tree with the tree density.

In December 1997, the sampling and analyzing were repeated with the similar manner, and the difference in tree biomass between the two samplings was taken as the annual biomass increment.

Definition and calculation of nutrient flux parameters

Nutrient retranslocation can be calculated with different methods (Helmisaari 1992). In this paper, the *retranslocation* (R, %), the degree of nutrient withdrawal from senescing needle, was defined as the following equation:

$$R(\%) = \frac{N_1 - N_2}{N_1} \times 100 \quad (1)$$

where N_1 (mg · g^{-1}) is nutrient concentration of mature needle, and N_2 (mg · g^{-1}) nutrient concentration of litter needle.

The quantity of nutrient withdrawn (W, g · m^{-2}) from litter fall was calculated with equation,

$$W = \frac{L \times (N_1 - N_2)}{1000} \quad (2)$$

where L is annual litter fall (g · m^{-2}), N_1 and N_2 are the same in the Formula (1), and 1000 is a conversion factor of microgram to gram.

The quantity of the nutrient fixed in biomass increment is termed as *retention* (g · m^{-2}), and the nutrient fluxes with the litterfall as *return* (g · m^{-2}). The *uptake* (g · m^{-2}) is the sum of retention and return. The *root-uptake* (g · m^{-2}) is estimated as the uptake minus the *withdrawal*.

Chemical analysis

For the nutrient analysis, a sub-sample of each biomass fraction was grounded to pass through a 1 mm sieve. All samples were digested with HNO_3-$HClO_4$-H_2SO_4 to determine the concentration of nitrogen, phosphorus, potassium, calcium and magnesium. Nitrogen was determined by distillation; Phosphorus with a colorimeter, potassium with a flame photometry; and calcium and magnesium with an atomic absorption spectrophotometer (Allen 1974; Nanjing Soil Science Institute 1978). The stand level nutrient content was then obtained by multiplying each biomass fraction with the respective nutrient concentrations and finally summing the contents in individual fractions.

Results

Litterfall

All the three investigated stands had a similar pattern of litterfall during the two years, peaking twice in the yearly cycle (March and December, Fig. 1). The highest monthly litterfall was 21-88 g · m^{-2}, and the lowest 5-13 g · m^{-2} in three stands. The annual litterfall was the highest in the mature stand (418 g · m^{-2} · a^{-1}), about 25% lower in the middle-aged stand (310 g · m^{-2} · a^{-1}), and only a quarter in the young stand (106 g · m^{-2} · a^{-1}). The differences of annual total litterfall between three stands were statistically significant (Table 3). The foliage litter made the biggest fraction of total litter mass, but the relative portion decreased with increasing stand age, being 60%, 56% and 49% in the young, middle-aged and mature stands, respectively.

Table 3. Annual litter production in different aged stands (mean ± s.e., n = 12), g.m^{-2}.y^{-1}

Stands	Foliage	Branch	Cone	Miscellany	Total
Young	64± 1.63	35±3.56	3±1.15	4± 2.83	106± 3.92*
Middle	175±10.86	79±4.42	44±2.41	12± 0.65	310±7.75*
Mature	205±3.16	120±7.46	68±6.53	25±3.09	418±13.25*

Note: * significant at α=0.001 for T-test

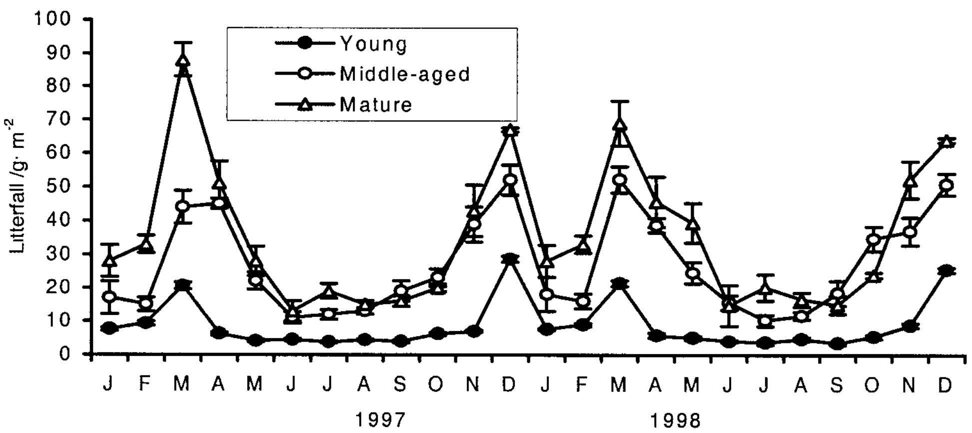

Fig. 1 Monthly variations of litter fall in three Chinese fir stands in 1997 and 1998
Note: Abbreviation of J to D is from January to December

Standing crop of biomass

The biomass in the mature stand was 1.7 times that in the middle-aged stand, and 2.7 times that in the young stand. Among the biomass fractions the stem was the biggest one in three stands. The percentage of stem mass increased with stand age, and correspondingly, the frac-

tions of foliage and branch biomass decreased in three stands (Table 4).

In all stands most resources were allocated to stem (48%-61%) and root (17%-22%) growth. With increasing stand age, fewer resources were allocated to foliage and branches, and more reproduction organs (Table 4).

Nutrient contents of biomass

The most abundant nutrient in tree biomass was nitrogen (13-29 $g \cdot m^{-2}$), and the least one was phosphorus (2-3 $g \cdot m^{-2}$) (Table 6). Among different biomass fractions, foliage had the highest content of nutrients, trunk (bark and stem wood) the second highest, and cone the lowest (Table 5).

Table 4. Biomass of three stands, $g \cdot m^{-2}$

Stands	Foliage	Branch	Cone	Bark	Stem	Root	Total
Young	600(11)	582((11)	52(1)	432(8)	2515(48)	1118(21)	5299(100)
Middle-aged	700(9)	602(7)	88(1)	741(9)	4278(52)	1851(22)	8260(100)
Mature	919(6)	749(5)	131(1)	1363(10)	8650(61)	2431(17)	14243(100)

Note: The numbers in parentheses are percentage of various biomass components in the total mass (%).

Table 5. Nutrient contents of biomass in three stands, $g.m^{-2}$

Elements	Foliage	Branch	Cone	Bark	Stem	Root	Total
			Young stand				
N	5.75(42)	2.28(16)	0.50(4)	1.14(8)	2.26(16)	1.93(14)	13.86(100)
P	0.55(25)	0.44(20)	0.03(1)	0.17(8)	0.70(32)	0.32(14)	2.21(100)
K	4.69(36)	3.27(25)	0.41(3)	1.05(8)	1.56(12)	2.02(16)	13.00(100)
Ca	4.18(31)	2.40(18)	0.19(1)	2.03(15)	2.21(17)	2.35(18)	13.36(100)
Mg	1.39(38)	0.82(23)	0.11(3)	0.20(6)	0.60(17)	0.49(13)	3.61(100)
			Middle-aged stand				
N	6.87(31)	2.78(13)	0.75(3)	2.57(11)	3.89(18)	5.35(24)	22.21(100)
P	0.78(28)	0.37(13)	0.06(2)	0.28(10)	0.81(29)	0.52(18)	2.82(100)
K	6.00(35)	3.08(18)	0.76(4)	1.66(10)	2.44(14)	3.26(19)	17.20(100)
Ca	6.64(33)	3.24(16)	0.43(2)	2.82(14)	2.27(11)	4.89(24)	20.29(100)
Mg	1.57(36)	0.81(18)	0.17(4)	0.30(7)	0.81(18)	0.76(17)	4.42(100)
			Mature stand				
N	8 28(28)	3.06(10)	1 05(4)	4.24(14)	6.92(24)	5.93(20)	29.48(100)
P	1.14(34)	0 38(11)	0 08(2)	0.46(14)	0.69(20)	0.63(19)	3.38(100)
K	7.97(34)	3.47(15)	1.08(5)	2.79(12)	4.33(18)	3.84(16)	23.48(100)
Ca	9.14(32)	3 84(14)	0.64(2)	4.93(18)	3.55(13)	6.00(21)	28.10(100)
Mg	1.97(33)	0.98(16)	0.26(4)	0.52(9)	1.38(23)	0 88(15)	5.99(100)

Note: The numbers in the parentheses are percentage (%) in the total.

Nutrient fluxes with biomass increment and litterfall

In all stands, N, P, K and Mg were withdrawn from senescing needles while Ca increased (Table 6). The nutrient retranslocation (R) were higher in the middle-aged and the mature stands than in the young stand except for magnesium. In the middle-aged and the mature stands, the retranslocation decreased in an order K > P > Mg > N. The concentration of Ca increase in the needle litter increased with stand age (Table 6).

Table 6. Retranslocation for various elements in senescing needles, %

Stands	N	P	K	Ca*	Mg
Young	1	21	9	-1	56
Middle-aged	24	52	61	-5	46
Mature	18	60	65	-10	49

Note: * Negative sign (-) represents nutrient increase in the needle litter when the needles were senescing

In the middle-aged stand the return of nutrients to soils with litterfall was more than twice the return in the young stand, and in the mature stand the return was even greater (Table 7). In three stands, Ca was most abundantly returned to soil followed in decreasing order by N, K, Mg and P. Among the litter components needle litter was the major nutrient carrier.

On annual basis, substantially more N, P, K and Mg were bound in biomass than these returned to soil in litter. In the case of Ca, return exceeded greatly retention in the middle-aged and mature stands, while in the young stand retention clearly exceeded the return (Table 7).

According to our estimation the nutrients Chinese fir needed were come from two sources, the uptake by root and withdrawal from senescing needles. The proportions of nutrients supplied through withdrawal varied widely both among elements and with stand age (Table 7). Generally, P, K and Mg were the internally most efficiently used elements and the relative importance of withdrawal increased with stand age.

Table 7. Retention, return, root-uptake and withdrawal of nutrients in three stands, g.m^{-2}.y^{-1}

Items	N	P	K	Ca	Mg
Young stand					
Retention	0.98	0.24	1.00	1.21	0.53
Return	0 74	0.07	0.61	0.63	0.10
Uptake	1.72	0.31	1 61	1.84	0.63
Root-uptake	1.71	0.30	1.56	1.85	0.55
Withdrawal	0.01	0.01	0.05	-0.01*	0.08
Middle-aged stand					
Retention	3.01	0.28	1.40	1.67	0.45
Return	2.11	0.15	1.10	2.60	0.42
Uptake	5.12	0.43	2.50	4.27	0.87
Root-uptake	4.70	0.33	1.58	4.35	0.69
Withdrawal	0 42	0.10	0.92	-0.08*	0.18
Mature stand					
Retention	3.40	0.31	1.46	1.75	0.33
Return	2.88	0.18	1.44	3.62	0.60
Uptake	6.28	0.49	2.90	5.37	0.93
Root-uptake	5.94	0.34	1.75	5.57	0.71
Withdrawal	0.34	0.15	1.15	-0.20*	0.22

Note: The quantity of the nutrient fixed in biomass increment is termed as *retention*, and the nutrient fluxes with the litterfall as *return*. The *uptake* is the sum of retention and return. The *root-uptake* is estimated as the uptake minus the *withdrawal*. * Negative sign (-) represents the accumulated nutrients in the needle litter when the needles were senescing.

Discussion

Litterfall

Several investigations have shown that litterfall in Chinese fir stands has bimodal distribution over a yearly cycle (Tian and Zhao 1989; Wu *et al.* 1990; Lian and Zhang 1998). The litterfall pattern in our study was consistent with these findings, but differences in peaking time. For instance, the first litterfall peak occurred in March in our stands, but in April or May in other stands studied (Tian and Zhao 1989; Wu *et al.* 1990).

The litterfall in our mature stand falls in between 250-537 g·m^{-2}·a^{-1} in the mature Chinese fir stands (including data in all the Regions of various Zones), and this quantity is very similar to that in *Pinus massoniana* stands, another important conifers in subtropical China (Wen et al. 1989; Wu *et al.* 1990). The litterfall in Chinese fir stands is much smaller compared with that of broad-leaved trees, e.g. *Castanopsis kawakamii* forest (1300 g·m^{-2}·a^{-1}), in our study area (Lian and Zhang 1998).

Standing biomass

According to climate conditions and timber production capacity, the area where Chinese firs grow is divided into three zones (the Northern Zone, the Middle Zone and the Southern Zone). The Zones are further divided into the Regions, and the Region into the Sub-Regions (Huang and Shen 1993). The Chinese fir plantations in Fujian Province represent two different Sub-Regions of the Middle Zone (Huang and Shen 1993), the Sub-Regions with the highest productivity, and the second-highest productivity. Our experimental stands were located in the Sub-Region of highest productivity.

For timber plantations, the proportion of stem in total biomass is of critical importance because it concerns both the commercial value of plantations and timber-harvesting impact on nutrient loss. In this study, the proportion of stem (bark and stem wood) in total biomass was 55~71% in three stands (Table 4). Pan *et al.* (1981) reported the 60% in the young stands, 80% in the middle-aged and the mature stands, and 87% in the over-mature stands (45 year old) in Huitong, Hunan Province. This was the highest stem proportion reported for Chinese fir stands. In contrast, the proportion of stem for some broad-leaved evergreens was only 40%~55% in subtropical area in China (Li et al. 1997).

Nutrient fluxes

The retranslocation rate varies with trees species, and with site fertility for the species (Helmisaari 1992; Ericsson 1994; Van Den Driessche 1984). Retranslocation from all sources can supply between 50% and 60% of the requirements for new growth of *Pinus nigra* and *maritima* (Miller 1984). In this study, the retranslocation of nutrients for Chinese fir increased with stand age (Table 6), and the retranslocation rates of P, K and Mg were about 50%-60% in the middle aged and mature stands. This was a medium level of nutrient withdrawal in conifers (Ericsson 1994).

Of various pathways, the nutrient flux via aboveground litterfall represents the majority of nutrient return to the soil (Lian and Zhang 1998). In this study, the magnitude of nutrient return through litterfall in different aged stands was consistent with observations by Pan *et al.* (1981) and Lian and Zhang (1998). Compared with broad-leaved forests in subtropical areas in China, the nutrient return in Chinese fir stands were slow due to the small amount of litterfall (Wu *et al.* 1990; Lian and Zhang 1998).

In our study, if the mature stand was clear-cutting at the age of 25 years, the timber extraction will cause a nutrient loss of 11 (N), 1 (P), 7 (K), 8 (Ca), and 2 (Mg) g.m^{-2}. On a rotation of 25 years, average yearly nutrient loss is 0.44 g·m^{-2}·a^{-1} for N, 0.04 g·m^{-2}·a^{-1} for P, 0.28 g·m^{-2}·a^{-1} for K, 0.32 g·m^{-2}·a^{-1} for Ca and 0.08 g·m^{-2}·a^{-1} for Mg. These values are just slightly less than the flux by nutrient withdrawal from the senescing aboveground tissues. Thus these nutrient losses can be serious to such continuously managed, pure Chinese fir plantations. Three processes regulating nutrient transfers have been recognized in studying the nutrient fluxes in forest ecosystems, 1) the geochemical cycle (in the soil), 2) the biogeochemical cycle (between trees and soil), 3) the biochemical cycle (inside the trees) (Ericsson 1994). In fact, the deposition of anthropogenic elements, fertilizer application and the nutrient loss by biomass harvesting forms the fourth nutrient cycling in plantations. The study of this nutrient cycle as a frame-

work will be very useful both in the understanding of nutrient balance and the nutrient management in such intensively managed and timber-oriented plantations.

Conclusions

Our results demonstrated that the experimental area is one of the highest productive Chinese fir plantations with high stem proportion in total biomass. Chinese fir is a low-nutrient-return species with litterfall. Nutrient withdrawal from senescing needles showed a strong age-dependence for nitrogen, phosphorous and potassium, and this plays a role in meeting nutrient need of older Chinese fir. In such Chinese fir plantations managed with short rotation and continuously pure-planting regime, harvesting timber results in serious nutrient losses, and this will degrade site fertility. In terms of nutrient balance, fertilisers are needed to maintain site productivity.

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